Soft Leptogenesis and Gravitino Dark Matter in Gauge Mediation

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Abstract

We study soft leptogenesis in gauge mediated supersymmetry breaking models with an enhanced A-term for the right-handed neutrino. We find that this scenario can explain the baryon asymmetry of the present universe, consistently with the gravitino dark matter for a wide range of gravitino mass $m_{3/2} = \mathcal{O}(\text{MeV})$–$\mathcal{O}(\text{GeV})$. We also propose an explicit model which induces the necessary A-term for the right-handed neutrino.

1 Introduction

Gauge-mediated supersymmetry breaking (GMSB) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10] is an attractive way of communicating supersymmetry (SUSY) breaking effects to the super-symmetric standard model (SSM), since flavor-changing neutral currents (FCNC) and dangerous CP violating phases are naturally suppressed. In addition, the mass spectrum of the superparticles in the SUSY standard model sector is determined by only a few parameters, which may be tested at the LHC in the near future.

In GMSB, the gravitino is the lightest SUSY particle and stable with R-parity. There-fore the gravitino is a candidate for the dark matter. In fact, gravitinos are produced by the scattering processes of thermal particles after the inflation [11, 12, 13], and its abundance is given by

$$\Omega_{3/2}h^2 \simeq 0.4 \times \left(\frac{m_{3/2}}{0.1\,\text{GeV}}\right)^{-1} \left(\frac{m_{\tilde{g}}}{1\,\text{TeV}}\right)^2 \left(\frac{T_R}{10^7\,\text{GeV}}\right), \tag{1}$$

where $\Omega_{3/2}$ and $m_{3/2}$ are the density parameter and the mass of the gravitino, respectively, $h \simeq 0.73$ is the normalized Hubble parameter, $m_{\tilde{g}}$ is the gluino mass, and T_R is the reheating temperature after the inflation. Therefore, the gravitino becomes a viable dark matter candidate for $T_R \lesssim \mathcal{O}(10^7)\,\text{GeV} \times (m_{3/2}/0.1\,\text{GeV})$, or it can explain the observed cold dark matter density, $\Omega_{\text{CDM}}h^2 \simeq 0.11$ [14], if the reheating temperature saturates the bound. Furthermore, the notorious inflaton–induced gravitino problem [15], which excludes most of the inflation models in the gravity–mediated SUSY breaking scenario, can be avoided in GMSB models.

However, another big puzzle in cosmology, the origin of the matter anti-matter asymmetry of the universe, is not easy to solve in this framework:

- In the standard thermal leptogenesis with heavy right-handed (RH) neutrinos [16], there is a lower bound on the mass of the RH neutrino, $M_N \gtrsim 2 \times 10^9\,\text{GeV}$ [17, 18], which requires a high reheating temperature $T_R > \mathcal{O}(10^9)\,\text{GeV}$. This would lead to a too much gravitino abundance for $m_{3/2} \lesssim \mathcal{O}(10)\,\text{GeV}$ [cf. Eq. (1)].

- Affleck-Dine baryogenesis [19, 20] can work with a low reheating temperature, but in GMSB it generically predicts a stable Q-ball [21, 22], and the parameter region is tightly constrained [23, 24].

- Electroweak baryogenesis [25, 26, 27] seems also difficult because the necessary ingredients, a first order phase transition and sufficient CP phases, are absent in GMSB.

In this paper, we would like to propose a viable baryogenesis scenario in GMSB, which is consistent with the gravitino dark matter for a wide range of gravitino mass $\mathcal{O}(\text{MeV})$–$\mathcal{O}(\text{GeV})$.[1] The framework is a simple GMSB model supplemented by an enhanced A-term for the RH neutrino, and the baryon asymmetry is produced by the soft leptogenesis [36, 37].

Soft leptogenesis [36, 37] is an attractive way of generating baryon asymmetry. The SUSY breaking terms introduce a mixing between the RH sneutrinos and their antiparticles. This induces significant CP violation in sneutrino decays in similar ways to B^0-$\bar{B}^0$ and K^0-$\bar{K}^0$ mixings. An attractive feature of the soft leptogenesis is that M_N (and T_R) can be smaller than that in the standard leptogenesis and therefore there is a possibility of generating baryon asymmetry without generating too much gravitino dark matter.

Interestingly, a successful soft leptogenesis favors a small B-term for the RH neutrino, which is naturally realized in the framework of GMSB [38]. In Ref. [38], the authors investigated the soft leptogenesis in a minimal GMSB setup, and found a viable parameter region with very light gravitino $m_{3/2} \lesssim 16\,\text{eV}$. In the minimal setup, the RH neutrino A-term is suppressed, and hence sufficient baryon asymmetry cannot be generated for $m_{3/2} \gtrsim \mathcal{O}(100\,\text{eV})$ satisfying the gravitino constraint. We extend their study with an enhanced A-term, and show that there is a viable region with $m_{3/2} = \mathcal{O}(\text{MeV})$–$\mathcal{O}(\text{GeV})$, consistently with the gravitino dark matter. We also show an explicit model which generates an enhanced A-term through the coupling between the messenger and up-type Higgs, without introducing additional unwanted CP phases in the low energy.

This paper is organized as follows: In section 2, we briefly review soft leptogenesis, and then show that the baryon asymmetry can be explained in our scenario. In section 3, we introduce a concrete model which generates the necessary A-term through a coupling between the up-type Higgs and the messenger. Section 4 is devoted to summary and discussion.

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[1]For other possibilities of baryogenesis and gravitino dark matter in GMSB, see, for instance, Refs. [28, 23, 29, 30, 31, 32, 33, 34, 35].

2 Soft Leptogenesis

Let us first briefly review the soft leptogenesis following Ref. [37]. We consider only the lightest RH neutrino and sneutrino for simplicity. The superpotential for the RH neutrino is given by

$$W = \frac{1}{2}M_N NN + Y_{\nu,i}L_i H_u N, \tag{2}$$

where N, L_i and H_u are the chiral superfields for the RH neutrino, the lepton doublets, the up-type Higgs, respectively. The soft SUSY breaking terms containing RH sneutrino $\tilde{N}$ are

$$-\mathcal{L}_{soft} = m_{\tilde{N}}^2 \tilde{N}^* \tilde{N} + \frac{B_\nu M_N}{2}\tilde{N}\tilde{N} + A_\nu Y_{\nu,i}\tilde{L}_i H_2 \tilde{N} + h.c.. \tag{3}$$

M_N and $Y_{\nu,i}$ are taken to be real by redefining the phases of the superfields, N and L_i. SUSY breaking terms introduce the mixing between $\tilde{N}$ and $\tilde{N}^*$, which induces lepton asymmetry in decays of $\tilde{N}$ and $\tilde{N}^*$. Then, the generated lepton asymmetry is converted into the baron asymmetry through the sphaleron process [39]. The baryon to entropy ratio is given by [37][2]

$$\frac{n_B}{s} \simeq 8.6 \times 10^{-4} \left[\frac{4\Gamma|B_\nu|}{4|B_\nu|^2 + \Gamma^2} \frac{|A_\nu|\sin\theta}{M_N} \right] \eta, \tag{4}$$

where Γ is the width of the RH sneutrinos

$$\Gamma \simeq \frac{|Y_{\nu,i}|^2}{4\pi}M_N, \tag{5}$$

θ is the CP phase given by $\theta = \arg(B_\nu A_\nu^*)$, and η is a factor which describes the effects caused by the inefficiency in the production of the RH sneutrinos, the wash-out effects, and the temperature dependence of the phase space of fermionic and bosonic final states in RH sneutrino decays. The maximum value of η is $\mathcal{O}(0.1)$ for $\widetilde{m_1} \simeq 10^{-(3-4)}$eV [37], where

$$\widetilde{m_1} = \frac{|Y_{\nu,i}|^2 v^2}{M_N}, \tag{6}$$

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[2]Here and hereafter, we neglect flavor effects [40], quantum effects [41], and corrections suppressed by $\mathcal{O}(m_{\text{soft}}/M_N)^2$ [42], for simplicity. These effects are small in most of the parameter region of our interest.

and $v = 174\,\text{GeV}$ is the vacuum expectation value of Higgs.

Now let us estimate the baryon asymmetry by using Eq. (4) in our setup. For simplicity, we assume $\widetilde{m_1} \simeq 10^{-3}\text{eV}$ and $\eta \simeq 0.1$,[3] which leads to

$$\Gamma \;\simeq\; \frac{\widetilde{m_1}}{4\pi v^2} M_N^2 \;\simeq\; 0.26\;\text{MeV} \left(\frac{M_N}{10^7\,\text{GeV}}\right)^2 . \tag{7}$$

We also assume that B_ν is dominated by the gravity-mediation contribution, $|B_\nu| \sim m_{3/2}$,[4] as discussed in Ref. [38]. Fig. 1 shows the region where a sufficient baryon asymmetry is generated in $m_{3/2}$–M_N plane. In the region enclosed by the red dotted line (green dashed line), n_B/s can explain the observed value $[n_B/s]_{\text{obs}} \simeq 8.7 \times 10^{-11}$ [14] for $B_\nu = 0.1m_{3/2}$ ($B_\nu = 0.01m_{3/2}$). Here, we have taken $A_\nu \simeq 1$ TeV (see discussion below). The upper (red dotted and greed dashed) lines show the upper bounds on M_N, $M_N^{\max} \propto B_\nu^{1/3}$, and the lower lines show the lower bounds $M_N^{\min} \propto B_\nu$. These behaviors can be understood from the fact that $n_B/s \propto M_N^{-3}B_\nu$ for $|B_\nu| \ll \Gamma$ and $n_B/s \propto M_N B_\nu^{-1}$ for $|B_\nu| \gg \Gamma$ [cf. Eqs. (4)(7)].

A successful leptogenesis requires $T_R \gtrsim M_N$. On the other hand, the maximal value of T_R, which is consistent with the dark matter abundance, is given by the requirement that $\Omega_{3/2} < \Omega_{CDM}$ [cf. Eq.(1)]. This leads to

$$M_N \lesssim \mathcal{O}(10^7\,\text{GeV}) \left(\frac{m_{3/2}}{0.1\,\text{GeV}}\right). \tag{8}$$

In Fig. 1, we have also shown the constraint $\Omega_{3/2}h^2 < 0.121$ [14] as a blue solid line, for $T_R = M_N$ and $m_{\tilde{g}} = 750$ GeV.[5] Around the blue solid line, the gravitino can be the dominant component of the dark matter.

Now we estimate the required size of A_ν. As discussed above, smaller M_N is favored by the constraint from the gravitino abundance, which corresponds to $\Gamma < |B_\nu|$ [cf. Eq.(7)]. By taking $\Gamma \ll |B_\nu|$, we obtain

$$\frac{n_B}{s} \simeq 2.2 \times 10^{-19} \frac{M_N}{|B_\nu|} \left(\frac{|A_\nu|}{1\text{TeV}}\right). \tag{9}$$

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[3] The precise value of η depends on the initial abundance of the RH sneutrino [37].

[4] The contribution from the anomaly mediation is also included.

[5] We have included Bino and Wino contributions to the gravitino production [13], assuming the GUT relation among gaugino masses.
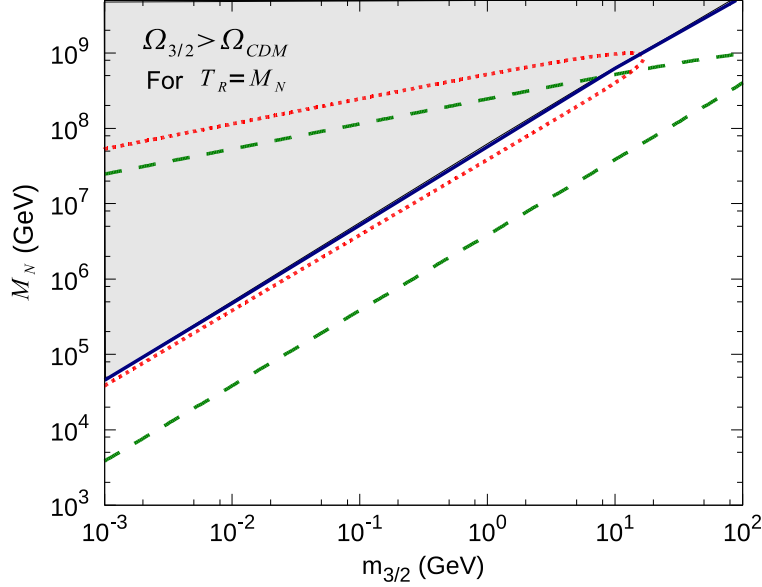
Figure 1: The region with successful baryogenesis is shown in $m_{3/2} - M_M$ plane. Sufficient baryon asymmetry can be generated in the region enclosed by the red dotted line (green dashed line) for $B_\nu = 0.1 m_{3/2}$ ($B_\nu = 0.01 m_{3/2}$). The gray region above the blue solid line is excluded due to too large abundance of the gravitino for $T_R = M_N$. We take $A_\nu = 1\,\mathrm{TeV}$ and $m_{\tilde{g}} = 750\,\mathrm{GeV}$.

From Eq. (8), this implies

$$\mathrm{max}\left(\frac{n_B}{s}\right) \simeq \mathcal{O}(10^{-11})\left(\frac{m_{3/2}}{|B_\nu|}\right)\left(\frac{|A_\nu|}{1\mathrm{TeV}}\right). \tag{10}$$

Therefore in order to explain the observed value of n_B/s, $|A_\nu| \simeq (100\,\mathrm{GeV} - 10\,\mathrm{TeV})$ is required for $|B_\nu| \simeq (0.01 - 1)m_{3/2}$. However, such a large A-term is not generated in a minimal GMSB. In fact, it was found [38] that a successful soft leptogenesis and the gravitino constraint require an ultralight gravitino $m_{3/2} \lesssim 16$ eV, as far as the A-term is generated through the renormalization–group evolutions. In the next section, we show an explicit model which can generate a large A-term for the RH neutrino.

3   A Model

In this section, we give a concrete model which generates the enhanced A_ν, through a new coupling between the messenger field and the up-type Higgs. We will also show that
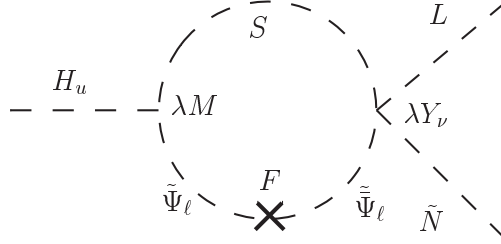
Figure 2: The Feynman diagram generating A_ν.

this coupling does not induce large CP violation.

In GMSB, the messenger mass is given by the following superpotential:

$$W = X\Psi\bar{\Psi}, \tag{11}$$

where Ψ and $\bar{\Psi}$ are messenger superfields and transform as $\mathbf{5}$ and $\bar{\mathbf{5}}$ under the GUT SU(5), respectively. X is a superfield which has a scalar and an auxiliary vacuum expectation values, $\langle X \rangle = M + F\theta^2$. We consider only one pair of messengers for simplicity, however an extension to the multi-messenger case is straightforward.

In order to generate the A-term, $\mathcal{L} = -A_\nu Y_\nu \tilde{L} H_u \tilde{N} + h.c.$, we consider the following superpotential [43, 44]:

$$W = \lambda S H_u \bar{\Psi}_\ell, \tag{12}$$

where $\bar{\Psi}_\ell$ is the leptonic part of the messenger $\bar{\Psi}$ and S is a gauge singlet. In order to forbid unwanted terms, such as $N H_u \bar{\Psi}_\ell$ and $N H_d \Psi_\ell$,[6] we introduce a messenger parity Z_2' in addition to the R-parity (equivalently matter parity). S, Ψ and $\bar{\Psi}$ are odd and the others are even under Z_2'. There is also another term, $\lambda' S H_d \Psi_\ell$, which is allowed by the symmetry. However, this term is irrelevant to the generation of A_ν, and therefore we neglect it in following discussion, for simplicity.

We take λ and the messenger mass M to be real by redefining the phases of Ψ and $\bar{\Psi}$. We assume that the mass of S, M_S satisfy the relation, $M_N < M_S < M$. The term in Eq.(12) decouples after integrating out the messenger superfields. The leading

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[6]If these term exist, the large B_ν can be generated.

contribution to the A-term which is proportional to (F/M) is given by the one-loop diagram expressed in Fig. 2. This contribution is also extracted from the wave-function renormalization of H_u by the analytic continuation method [43]. The leading term of A_ν is given by

$$A_\nu \simeq \left.\frac{\partial \ln Z_{H_u}}{\partial \ln X}\right|_{X=M} \frac{F}{M} = -\frac{\lambda^2}{16\pi^2}\frac{F}{M},\tag{13}$$

which can be of the order of $100\,\text{GeV} - 1\,\text{TeV}$.

Next we discuss the possible source of CP violation induced by the new coupling in Eq. (12). In addition to A_ν, this coupling generates A-terms for up-type squarks A_u, Higgs B-term B and soft SUSY breaking mass for up-type Higgs $m^2_{H_u}$ and squarks $m^2_{\tilde{Q}}$, $m^2_{\tilde{U}}$. The $m^2_{H_u}$, $m^2_{\tilde{Q}}$ and $m^2_{\tilde{U}}$ do not induce an additional CP phase beyond the CKM phase. A_u and B are given by

$$A_u = B \simeq -\frac{\lambda^2}{16\pi^2}\frac{F}{M}.\tag{14}$$

The corresponding terms in the superpotential and soft breaking terms are defined by

$$W = Y_{u,ij}Q_iH_u\bar{U}_j - \mu H_dH_u, \quad -\mathcal{L}_{soft} = A_uY_{u,ij}\tilde{Q}_iH_u\tilde{\bar{U}}_j - B\mu H_dH_u + h.c..\tag{15}$$

We assume that the Higgs μ term is generated above the messenger scale. Under this assumption, there is no physical phase from GMSB, since the phases of the soft breaking parameters are the same, $\arg(F/M)$ and we can remove them by the $U(1)_R$ transformation. On the other hand, the neutrino B-term, B_ν is generated by the gravity-mediation and the order of gravitino mass. Therefore its phase is expected to be completely different from $\arg(F/M)$. With the $U(1)_R$ transformation and a phase transformation of H_u, the parameters transform as,

$$\mu \to \mu e^{i(\theta_{H_u}-2\theta_R)}, \quad B_\nu \to B_\nu e^{2i\theta_R},$$
$$A_{\nu,u} \to A_{\nu,u}e^{2i\theta_R}, \quad B\mu \to B\mu e^{i\theta_{H_u}}.\tag{16}$$

If we choose $2\theta_R = -\arg(F/M)$ and $\theta_{H_u} = -\arg(\mu) - \arg(F/M)$, only B_ν is complex and its phase is $\arg(B_\nu F^*/M)$. Therefore the new interaction term does not lead to large CP violation in low energy phenomena.

4 Summary and Discussion

We considered soft leptogenesis in gauge mediated SUSY breaking scenario, including the simple interaction term which contains up-type Higgs and leptonic part of the messenger. The interaction term generates A_ν, A_u, soft SUSY breaking mass for up-type Higgs and squarks, and Higgs B-term. With the large A_ν soft leptogenesis works successfully, which is consistent with the gravitino dark matter for a wide range of gravitino mass. The phases of A_ν, A_u and Higgs B-term are aligned with those of other SUSY breaking terms from gauge mediated SUSY breaking. Therefore inclusion of the new interaction term does not lead to large CP violation in low energy phenomena. Interestingly, the additional contributions to the soft terms lead to a different spectrum pattern of SUSY particles from that of ordinary gauge mediation, which may be tested at LHC in the near future.

Acknowledgements

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